Ultra-Short Baseline Positioning System for Littoral Swarm Systems

Chris Casey
IS Robotics, Inc.
22 McGrath Highway, Suite 6
Somerville, MA 02143
phone: (617) 629-0055   e-mail: cmcasey@isr.com
http://www.isr.com
Award #: N0001497C0288

Dr. James G. Bellingham
Massachusetts Institute of Technology (MIT)
Sea Grant College Program
Cambridge, MA 02139
phone: (617) 253-7136   fax: (617) 258-5730   e-mail: belling@mit.edu

LONG-TERM GOAL

The long-term goal of the Distributed Acoustic Mobile Positioning (DAMP) program is to develop a positioning system for use in littoral regions. The system will operate in a variety of conditions and will form the cornerstone of a multi-vehicle positioning and navigation system.

OBJECTIVES

We seek to implement such a system using an ultra-short baseline (USBL) positioning system to provide bearing information along with a round-trip time-of-flight measurement protocol to provide range information. In order to be useful for the systems contemplated (swarms of robots), such a system must be inexpensive, small, lightweight, and energy efficient. Characterization of the surf zone (SZ) acoustic environment will be necessary in order to effectively select operating parameters such as frequency and intensity of the USBL system, however, the main objective of DAMP is to create a workable and working USBL system operable in the very shallow water (VSW) and SZ environments. One application of this technology is to VSW/SZ mine remediation.

APPROACH

Dr. James G. Bellingham at MIT Sea Grant undertook theoretical work and performed simulations to gauge the impact of relative position information on the effectiveness of searches conducted by swarms of robots. Additional simulation work was performed under the direction of Professor Henrik Schmidt, also at Sea Grant, to begin the characterization the surf zone acoustic environment necessary to set baseline operating parameters for the USBL system.

At IS Robotics, work was undertaken by Chris Casey to evaluate design approaches and to establish a reference design for the USBL system. Analog and DSP-based approaches were evaluated for both cost and effectiveness. The emphasis in this evaluation was on cost, as the final system had to be inexpensive in order to be a worthwhile addition to a swarm member robot. This is reinforced in mine searching applications because of the likelihood that the searcher will be destroyed in the process of

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removing the mine. A reference design for the chosen approach was then completed to the schematic level. A technique for acquiring range information to supplement the bearing information provided by the USBL system was developed. Simulations were performed to estimate technique effectiveness and the effects of losses in position information caused by background noise, interference, etc.

MIT and IS Robotics personnel tested a commercially available USBL system to evaluate its performance in very shallow water.

WORK COMPLETED

Dr. James G. Bellingham at MIT Sea Grant has demonstrated that adding navigation capabilities to vehicles can improve the efficiency of swarm behaviors, including searching, over that obtained from searchers moving purely randomly.

ISR and MIT personnel have demonstrated experimentally that a commercial off-the-shelf USBL system can operate acceptably even in very shallow water.

Chris Casey at IS Robotics has defined a reference design for a small, low-power USBL system.

We have defined a challenge/response protocol that allows swarm members to estimate distances between swarm members.

ISR has conducted simulations to determine the effects of lost position samples on swarm cohesion and spacing.

Work has begun under the direction of Henrik Schmidt at MIT Sea Grant to provide sufficient characterization of the VSW/SZ acoustic environment to allow selection of acceptable (although not necessarily optimal) operating parameters for the USBL system.

RESULTS

Navigation

Work performed by Dr. Bellingham demonstrates that relative position information can be used to increase dramatically the effectiveness with which swarms of robots search for mines. Randomly moving robots must balance the need for rapid diffusion from a central deployment point to avoid over-searching one area with the need to diffuse slowly in order to stay within the search area. The use of relative position information allows robots to rapidly diffuse from a central deployment point, without diffusing completely out of the search zone. Swarm members can be programmed with a preferred distance between themselves and other searchers. This allows them to diffuse rapidly when they are tightly clumped, but then to stop diffusing once an appropriate distance is reached. If the searcher population is declining (as would be the case if members park themselves next to detected mines in preparation for sympathetic detonation), the notion of a preferred distance allows the swarm to "heal" itself of holes created as searchers drop out.

USBL Implementation

ISR and MIT Sea Grant conducted experiments with an off-the-shelf commercial USBL system in very shallow (less than 1m) still water. These experiments indicated that the system operated acceptably from ranges of 25m to approximately 400m. While sufficiently adverse conditions in the surf zone will undoubtedly degrade USBL effectiveness, it is clear that, for at least some conditions, a USBL system is a viable solution to relative navigation.

Available off-the-shelf USBL systems are relatively expensive, large, and power-consumptive and are thus not suitable for use in small robots. The current state of the art of electronics permits the design of a small, low-cost, low-power USBL-based navigation system. We evaluated two approaches to such a design, one analog, the other using a digital signal processor (DSP).

In the DSP-based approach, a high-speed analog to digital converter was used to digitize the incoming signals from four hydrophones. The digitized data were then fed to a DSP that performed the signal analysis to determine the phase difference between the hydrophones and thus estimate the bearing to the sound source.

The analog approach is a substantially simpler. The incoming signals from the hydrophones are band-limited and then amplified and clipped. These signals are compared using a simple programmable logic device to determine difference in arrival times of the sound. Further band-limiting and RMS-DC conversion is used to generate a threshold output indicating when the phase comparison is valid. While this approach is less flexible than a DSP-based approach, it is also significantly cheaper.

We conclude that a USBL system based on a simple, low-cost, low-power analog design will provide sufficient capability to allow its use as the basis for a relative navigation system on underwater robots.

A schematic-level reference design for the chosen approach has been completed. Final component selection is awaiting further characterization of the acoustic environment, and subsequent selection of operating parameters.

Challenge/Response Protocol

An algorithm that allows robots to determine their distance from each other without unacceptable error accumulation even over extended missions has been defined.

Each member of the swarm will take turns issuing a "challenge" consisting of an acoustic ping differentiable from a "response" ping. Each swarm member that detects a challenge ping immediately issues a response ping. The challenger uses these response pings to determine both the bearing of each responder (using the USBL system), and the range (by determining the round-trip time of flight). This approach removes the need for each swarm member to have expensive, tightly synchronized clocks.

The length of time associated with each challenger must be long enough to allow the challenger's ping to propagate to its maximum distance and to allow the ping from a responder to propagate back to the challenger. In addition, a small guard region must be added to this time-slice in order to allow for clock drift between swarm members. This guard region ensures that robots do not violate each other's assigned time slice even if their clocks drift somewhat over the course of a mission.

Additional simulations performed at ISR showed that even when a large portion of position samples is lost (as would result from noise, or acoustic interference, for example), swarms were able to maintain cohesion and avoid clumping. Even in cases in which 80% of position updates were lost, the swarm as a whole remained remarkably stable.

Based on these simulations, we conclude that the challenge/response protocol represents a good solution to the problem of determining both bearing and range.

Acoustic Characterization

Developing a workable USBL system will require several design goals to be met. Challenge and response pings must be differentiable, and must be detectable under the conditions typically encountered in the VSW/SZ environment. However, the detection range of both challenges pings and response pings must be limited for optimal swarm performance. If these distances are not limited, long time periods must be assigned to each challenger, limiting the number of challenges which can be issued per time period, and thus reducing the position update rate within the swarm. If this position update rate is not kept sufficiently high, the swarm as a whole may go "out of control" and members may stop maintaining appropriate distances from each other.

Work is underway in MIT's Department of Ocean Engineering to begin determining an appropriate choice of frequency and intensity for both challenge and response pings. Initial simulations using OASES, a seismo-acoustic wave propagation modeling program, are being conducted to characterize the acoustic environment. Preliminary results from these simulations indicate that the height of the transmitter above the bottom has a large impact on transmission range. Transmitters located close to the bottom (0.1m) can attenuate transmitted signals significantly. Signals located at higher elevations do not suffer this effect.

IMPACT/APPLICATION

The development of a cheap relative navigation system as here envisioned would enable the implementation of swarm behaviors in underwater robots. This has application in a variety of areas, ranging from mine clearance to physical survey and mapping.

RELATED PROJECTS

Ariel, an underwater walking robot, is being developed under ONR sponsorship. Ariel will be the test platform used to develop and test the DAMP system

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